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Mid-late Holocene El Nino variability in the equatorial Pacific from coral microatolls

Abstract

Oxygen isotope ratios in *Porites* microatolls from Christmas Island in the central Pacific provide high-resolution proxy records of El Niño-Southern Oscillation (ENSO) variability since 3.8 thousand years ago (ka). Compared with modern microatolls, reconstructions from fossil microatolls imply that interannual variations in ENSO sea-surface temperature and precipitation were less intense 3.8–2.8 ka, but more pronounced at 1.7 ka. Amplification of ENSO at ~2 ka is consistent with precessional changes in insolation seasonality, but exceeds model predictions and may reflect stronger rainfall teleconnections through enhanced interaction between the Southern Oscillation and the Pacific Intertropical Convergence Zone.

Keywords

late, coral, mid, pacific, equatorial, variability, nino, el, holocene, microatolls, GeoQuest

Disciplines

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Mid-late Holocene El Niño variability in the equatorial Pacific from coral microatolls

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[1] Oxygen isotope ratios in *Porites* microatolls from Christmas Island in the central Pacific provide high-resolution proxy records of El Niño-Southern Oscillation (ENSO) variability since 3.8 thousand years ago (ka). Compared with modern microatolls, reconstructions from fossil microatolls imply that interannual variations in ENSO sea-surface temperature and precipitation were less intense 3.8–2.8 ka, but more pronounced at 1.7 ka. Amplification of ENSO at ~2 ka is consistent with precessional changes in insolation seasonality, but exceeds model predictions and may reflect stronger rainfall teleconnections through enhanced interaction between the Southern Oscillation and the Pacific Intertropical Convergence Zone. **INDEX TERMS:** 1620 Global Change: Climate dynamics (3309); 4870 Oceanography: Biological and Chemical: Stable isotopes; 4522 Oceanography: Physical: El Niño; 9355 Information Related to Geographic Region: Pacific Ocean; **KEYWORDS:** Coral paleoclimatology, Sea surface temperature, ENSO, Equatorial Pacific Ocean, Holocene. **Citation:** Woodroffe, C. D., M. R. Beech, and M. K. Gagan, Mid-late Holocene El Niño variability in the equatorial Pacific from coral microatolls, *Geophys. Res. Lett.*, 30(7), 1358, doi:10.1029/2002GL015868, 2003.

1. Introduction

[2] El Niño-Southern Oscillation (ENSO) events apparent in central equatorial Pacific sea-surface temperature (SST) have far-reaching effects on tropical and extra-tropical climate [Rasmusson and Carpenter, 1982]. ENSO events are quasi-cyclic from 2 to 7 years, with an average period of about 4 years. Changes in the magnitude and frequency of ENSO events observed in instrumental records since the 1970s have generated considerable debate about recent ENSO behaviour [Trenberth and Hoar, 1996], and the possibility that it may be responding to global warming [Timmermann *et al.*, 1999]. Proxy records of tropical climate, such as stable isotope ratios in massive corals, also indicate interdecadal variability in the intensity of ENSO during the last ~400 years [Dunbar *et al.*, 1994]. Further back in the Holocene, the nature and timing of the onset of ENSO is a matter of considerable debate. Numerical climate models suggest that orbitally driven changes in seasonal insolation produced slightly smaller and less frequent ENSO events in the early Holocene, which then steadily increased in intensity and frequency to a maximum at ~3–1 ka

[Clement *et al.*, 2000]. Geoarcheological evidence from South America [Sandweiss *et al.*, 1996], Ecuadorian varved lake sediments [Rodbell *et al.*, 1999], and corals from Papua New Guinea [Tudhope *et al.*, 2001] indicate that ENSO events were considerably weaker or absent between 8.8 and 5.8 ka. Faunal remains from archeological sites in Peru [Sandweiss *et al.*, 2001] indicate that the onset of modern, rapid ENSO recurrence intervals was achieved only after ~4–3 ka. However, a central issue limiting our understanding of the onset of ENSO is that it has not been possible to obtain detailed paleoclimate data capable of revealing the nature of ENSO in the central Pacific.

[3] We demonstrate that skeletal oxygen isotope ratios ($\delta^{18}\text{O}$) in fossil coral microatolls from Christmas (Kiritimati) Island in the central Pacific can be used to monitor variability in ENSO events over recent millennia. Christmas Island lies within the dry equatorial zone of the central Pacific (157°30'W, 2°00'N) on a sharp SST and rainfall gradient. The island experiences pronounced interannual variations in SST, sea level and rainfall that are ENSO-related (Figure 1a–c). Mean monthly SST varies from ~30°C to ~24°C between El Niño and La Niña years, respectively. Thus Christmas Island is particularly well-placed to capture a large proportion of the El Niño-La Niña SST variation, and represents an optimum site for monitoring ENSO [Evans *et al.*, 1998b]. Superimposed on this SST variability are strong interannual variations in annual rainfall (936 mm), which reached a maximum of 3686 mm during the El Niño event of 1997.

2. Field and Laboratory Methods

[4] Detailed geochemical analyses of massive coral skeletons provide insight into past SST and precipitation at time-scales spanning weeks to millennia [Gagan *et al.*, 1998, 2000]. However, fossil corals used to investigate Holocene paleoclimatological conditions are difficult to find in the central equatorial Pacific where Holocene uplift is absent and dead corals are buried by subsequent reef growth. By contrast, microatolls are corals that grow at the reef-atmosphere interface and fossil specimens are often more accessible across the Indo-Pacific reef province than massive hemispherical corals. Microatolls adopt a predominantly lateral growth form, constrained in their upward growth by exposure at lowest tides and, when their horizontal growth axis is sampled, offer a sea-surface proxy climate record.

[5] Christmas Island is a large, low-lying atoll, fringed by a narrow reef flat. Fossil microatolls grew within an

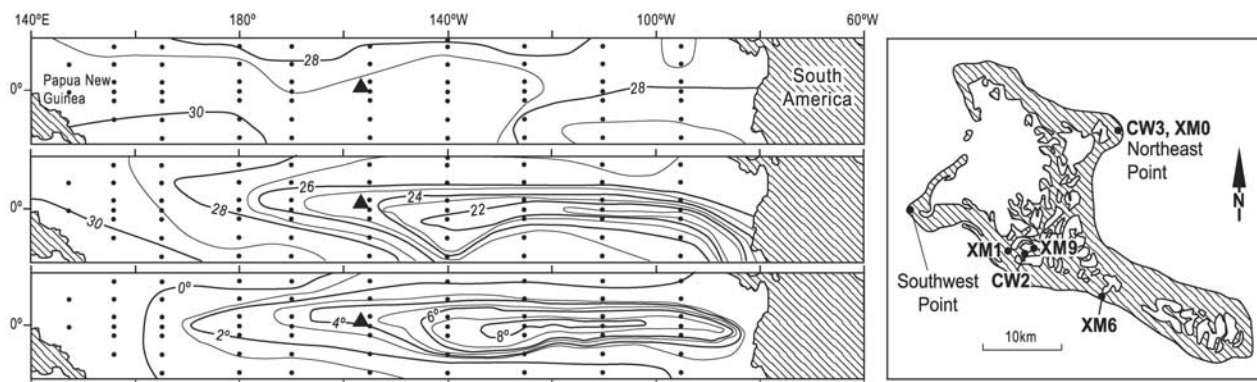


Figure 1. Central equatorial Pacific Ocean (10°N to 10°S) showing monthly averaged SST (°C) derived from TOGA-TAO array data. (a) El Niño conditions during December 1997; (b) La Niña conditions during December 1998; and (c) difference between a and b. (d) Christmas Island showing location of live and fossil microatolls sampled.

extensive lagoon in the island interior (Figure 1d) when sea level was relatively higher than present [Woodroffe and McLean, 1998]. Density banding revealed through X-radiographs and computer tomography (CT) scans of slices of the microatolls confirm lateral growth. Radiocarbon dating indicates that conditions appear to have been favourable for microatoll formation 3800–2800 ^{14}C years BP (mid-Holocene) and 2000–1500 ^{14}C years BP (late Holocene).

[6] Microatoll slices CW3 and CW2 were sampled at 0.25 mm increments and every 4th or 8th sample was analysed to achieve approximately monthly resolution [Woodroffe and Gagan, 2000]. Subsequent microatoll slices were cut to 6-mm thickness and were sampled at 3 mm or 1.5 mm intervals using an engraver. The modern microatoll chronology is based on X-radiography and linear interpolation between surface microtopography peaks that correspond to ENSO-induced regional sea-level highs, together with peak matching of skeletal $\delta^{18}\text{O}$ and IGOSS SST [Reynolds and Smith, 1994]. Average extension rate appears to have been 18.5 mm yr^{-1} for CW3 and 23.3 mm yr^{-1} for XM0. Neither X-radiography nor isotope analysis provide unambiguous annual chronologies in fossil corals, but growth rates appear to have averaged 20 mm yr^{-1} in CW2, 11.8 mm yr^{-1} in XM1, 14.3 mm yr^{-1} in XM6 and 15.2 mm yr^{-1} in XM9. Isotopic measurements were made at ANU using an automated individual-carbonate reaction (Kiel) device coupled with a Finnigan MAT-251 mass spectrometer. Isotope ratios are reported as per mil (‰) deviations relative to Vienna - Pee Dee belemnite (V-PDB) and calibrated using National Bureau of Standards NBS19, with internal precision of 0.06‰. Coral XM6 was analysed similarly at the University of Wollongong.

[7] Radiocarbon ages (Australian National University, Beta Analytic) were reservoir-corrected (450 ± 35 years) and have been converted to ^{14}C years before the present using the CALIB program (<http://calib.org/calib>).

3. Modern Microatolls and SST

[8] Modern analogue microatolls of the coral genus *Porites* were examined around Christmas Island in June 1991 and November 1999. The upper surface of most microatolls was observed to have responded to recent ENSO-related sea-level oscillations, as shown by other

reef-flat microatolls in this part of the Pacific [Woodroffe and McLean, 1990]. During El Niño years, when sea level is elevated, Christmas Island microatolls grow several millimetres higher into the intertidal zone. Microatoll growth descends to a lower level when regional sea level drops after an El Niño event. One modern microatoll specimen (CW3) from just landward of the reef crest at Northeast Point (Figure 1d) was sectioned and a slice was subsampled for stable isotope analysis [Woodroffe and Gagan, 2000]. Another microatoll colony (XM0) within the same field was sampled in 1999, together with fossil microatolls from the island interior.

[9] Figure 2a shows the composite modern microatoll $\delta^{18}\text{O}$ record for the period 1978 to November 1999. The period of overlap for the two coral records (February 1989 to June 1991) shows a good correlation ($r = 0.69$, $p = 0.01$), indicating dependable reproducibility between individual coral microatolls from the same site. The mean $\delta^{18}\text{O}$ value is slightly different for the two microatolls (−5.0‰ for CW3 and −5.2‰ for XM0), reflecting warmer SSTs during

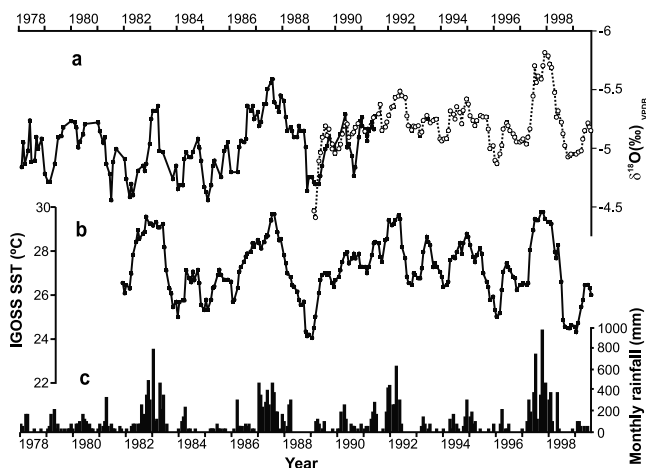


Figure 2. (a) Composite time-series (1978–99) of skeletal $\delta^{18}\text{O}$ values in modern *Porites* microatolls from the reef flat at Northeast Point (see Figure 1d), CW3 (solid dots [Woodroffe and Gagan, 2000]) and XM0 (open dots). (b) IGOSS SST (centered on 157°30'W, 1°30'N). (c) Monthly rainfall at Christmas Island.

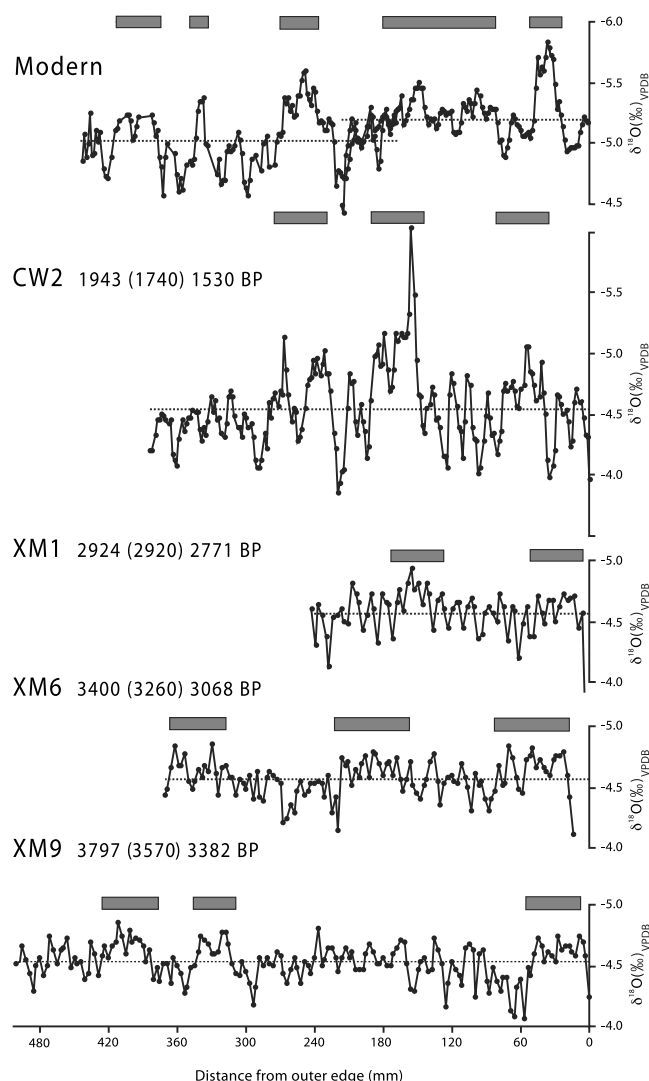


Figure 3. Comparison of profiles of skeletal $\delta^{18}\text{O}$ in modern (CW3, XM0), late-Holocene (CW2 [Woodroffe and Gagan, 2000]), and mid-Holocene (XM1, XM6, XM9) *Porites* microatolls from Christmas Island. Periods of lower $\delta^{18}\text{O}$ (warmer/wetter) indicative of El Niño events are shown by horizontal bars. Distance has been retained as the x axis, because several years cannot be unambiguously defined from banding or variations in $\delta^{18}\text{O}$. Two sigma range of calibrated radiocarbon ages in years BP.

the prolonged 1990–5 El Niño. The $\delta^{18}\text{O}$ records fluctuate from -4.6‰ to -5.6‰ for CW3 and -4.4‰ to -5.8‰ for XM0. There is a strong correlation between $\delta^{18}\text{O}$ and increases in SST and rainfall (Figure 2b and 2c) during El Niño years [Evans *et al.*, 1998a; Woodroffe and Gagan, 2000]. The El Niño of 1997–8 and the severe cooling during the 1998 La Niña are accurately recorded, as is the persistent, low amplitude El Niño event of 1990–5. Coral XM0 records the peak of the 1988–9 La Niña event, which is not so apparent in the CW3 record.

[10] Our results agree with comparisons of paired Sr/Ca and $\delta^{18}\text{O}$ measurements for 1981–7 from the skeleton of a massive *Porites* sampled at 9 m depth off Southwest Point, which indicate that coral $\delta^{18}\text{O}$ is primarily recording SST, with secondary salinity effects through direct dilution of

seawater with ^{18}O -depleted rainfall, or eastward advection of low salinity water [Evans *et al.*, 1998a, 1999]. A strong correlation has also been shown between proxy ENSO records from a Christmas Island coral, called NINO-C, and the NINO3 index for the area bounded by 150°W – 90°W , 5°N – 5°S . Based on these results, we extend the NINO-C index back in time using fossil microatolls which flourished in the former lagoon of Christmas Island.

4. Mid and Late Holocene Microatolls

[11] Figure 3 shows the composite $\delta^{18}\text{O}$ record for the modern microatolls compared with records for several fossil *Porites* microatolls from Christmas Island. The fossil corals all show a similar mean $\delta^{18}\text{O}$ value ($-4.53 \pm 0.02\text{‰}$), indicating a similar ocean temperature and salinity throughout the time period. Although potentially indicating water temperatures $\sim 2.5^{\circ}\text{C}$ cooler than present, the magnitude of any difference is unclear because the fossil corals may have grown within an evaporating, saline and ^{18}O -enriched lagoon, whereas the modern microatolls grow on reef flat continually flushed by open-ocean waters. The pattern of water temperature changes experienced in the paleo-lagoon in the late Holocene was evidently modulated by ENSO.

[12] Low amplitude oscillations occur representing probable El Niño events (Figure 3). Growth rates in XM1, XM6 and XM9 appear substantially slower than in more recent corals, but ENSO events appear to have persisted for 2–3 years, and occurred with similar periodicity as in the modern.

[13] The $\delta^{18}\text{O}$ ranges indicated by the mid-Holocene (XM1, XM6 and XM9) microatoll records are significantly smaller (average SD: 0.15‰) than those of the modern corals (average SD: 0.22‰) and much less than that at around 1.7 ka (CW2, SD: 0.31‰). During the late-Holocene at least one distinct El Niño event occurred with average $\delta^{18}\text{O}$ 0.3 – 0.6‰ lower (1.5 – 3°C warmer) than the non-El Niño average. This negative $\delta^{18}\text{O}$ excursion to -6.0‰ may reflect enhancement of the SST-induced $\delta^{18}\text{O}$ anomaly by substantial addition of ^{18}O -depleted rainfall [Woodroffe and Gagan, 2000].

5. Discussion

[14] A transition from reduced mid-Holocene to enhanced late-Holocene El Niño amplitude is predicted by numerical climate models (Figure 4a) as a consequence of altered solar radiation linked to precession of the Earth's orbit [Clement *et al.*, 2000]. However, our data indicate a change in ENSO magnitude that exceeds that attributable to precessional forcing alone (generally $<0.5^{\circ}\text{C}$ [Clement *et al.*, 2000]), and imply that instead of a gradual increase in ENSO variation there has been at least one unexpectedly abrupt shift to amplified ENSO variability during the late Holocene (Figure 4b). Although ocean-atmosphere models incorporate some feedbacks beyond the equatorial Pacific [Bush, 2001; Otto-Bliesner, 1999], such as the effect of the Asian monsoon and changes in depth of the thermocline, they remain constrained in regard to other boundary conditions. For example, abrupt shifts in the location of the Intertropical Convergence Zone (ITCZ) have recently been inferred from paleoclimatic data from South America [Haug *et al.*, 2001]. Figure 4c shows titanium concentrations in sediment from ODP site 1002 in the Cariaco Basin indicating abrupt

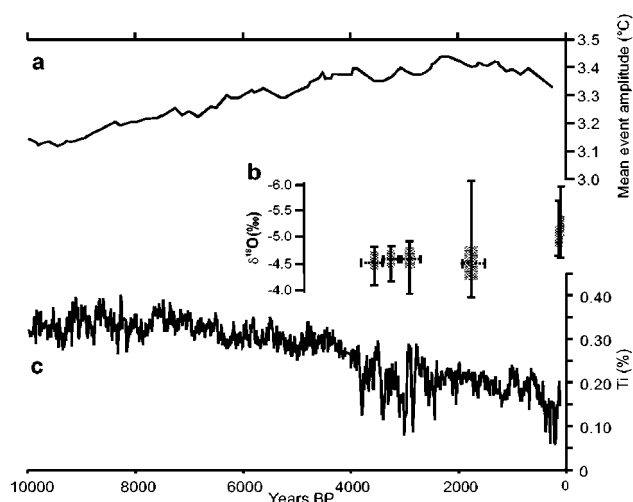


Figure 4. (a) Amplitude of modelled El Niño SST anomalies, based on precessional forcing [Clement *et al.*, 2000], showing maximum at ~2 ka. (b) Mean, standard deviation (shaded box), and range (vertical bars) of $\delta^{18}\text{O}$ for Holocene and modern microatolls from Christmas Island. Horizontal lines indicate 2 sigma range of calibrated radiocarbon ages. (c) Titanium concentration in deep-sea sediment at ODP Site 1002 as a proxy record of river runoff to the Cariaco Basin, South America [Haug *et al.*, 2001].

century-scale variations in runoff associated with shifts in the position of the ITCZ during the period 3.8–2.8 ka, contrasting with lower runoff and titanium input during the late Holocene when the ITCZ adopted a more southerly location [Haug *et al.*, 2001]. Further support for this hypothesis comes from higher lake levels at Lake Titicaca between 3.5–2.9 ka, reaching a maximum at ~2 ka when we observe maximum amplitude in ENSO [Baker *et al.*, 2001].

[15] We propose that the southward migration of the Pacific ITCZ during the Holocene produced an abrupt non-linear increase in ENSO amplitude through enhanced interaction of the locus of tropical atmospheric convection with the Southern Oscillation. During the mid-Holocene, when the mean position of the ITCZ was located further north, ENSO variations at Christmas Island may have been primarily temperature driven with a reduced range. At this time, interaction between the Southern Oscillation and ITCZ rainfall appears weak, as indicated by unexpectedly low precipitation variability observed in terrestrial paleoclimate records from the southern hemisphere tropics [Haug *et al.*, 2001]. In contrast, after 2.4 ka tighter coupling in the Pacific between the more southerly ITCZ and the Southern Oscillation could serve to amplify ENSO precipitation variability and associated teleconnections. Such a scenario is consistent with terrestrial paleoclimate records indicating a marked increase in El Niño activity ~3 ka [Rodbell *et al.*, 1999; Sandweiss *et al.*, 2001].

[16] Our results demonstrate the reliability of $\delta^{18}\text{O}$ in modern and fossil microatolls as a high-resolution multi-decadal proxy related to ENSO, implying non-linear changes in SST and precipitation in the equatorial Pacific during the Holocene. Individual ENSO events in the late Holocene appear at least as intense as those experienced in

the past two decades. It remains difficult to determine changes in background climate state. A framework within which variations in ENSO behavior can be related to time-averaged wind intensity and spatially-averaged depth of the thermocline has recently been proposed [Fedorov and Philander, 2000]. Examination of more fossil microatolls in the equatorial Pacific may clarify interactions between ENSO and changes in the mean position of the ITCZ.

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